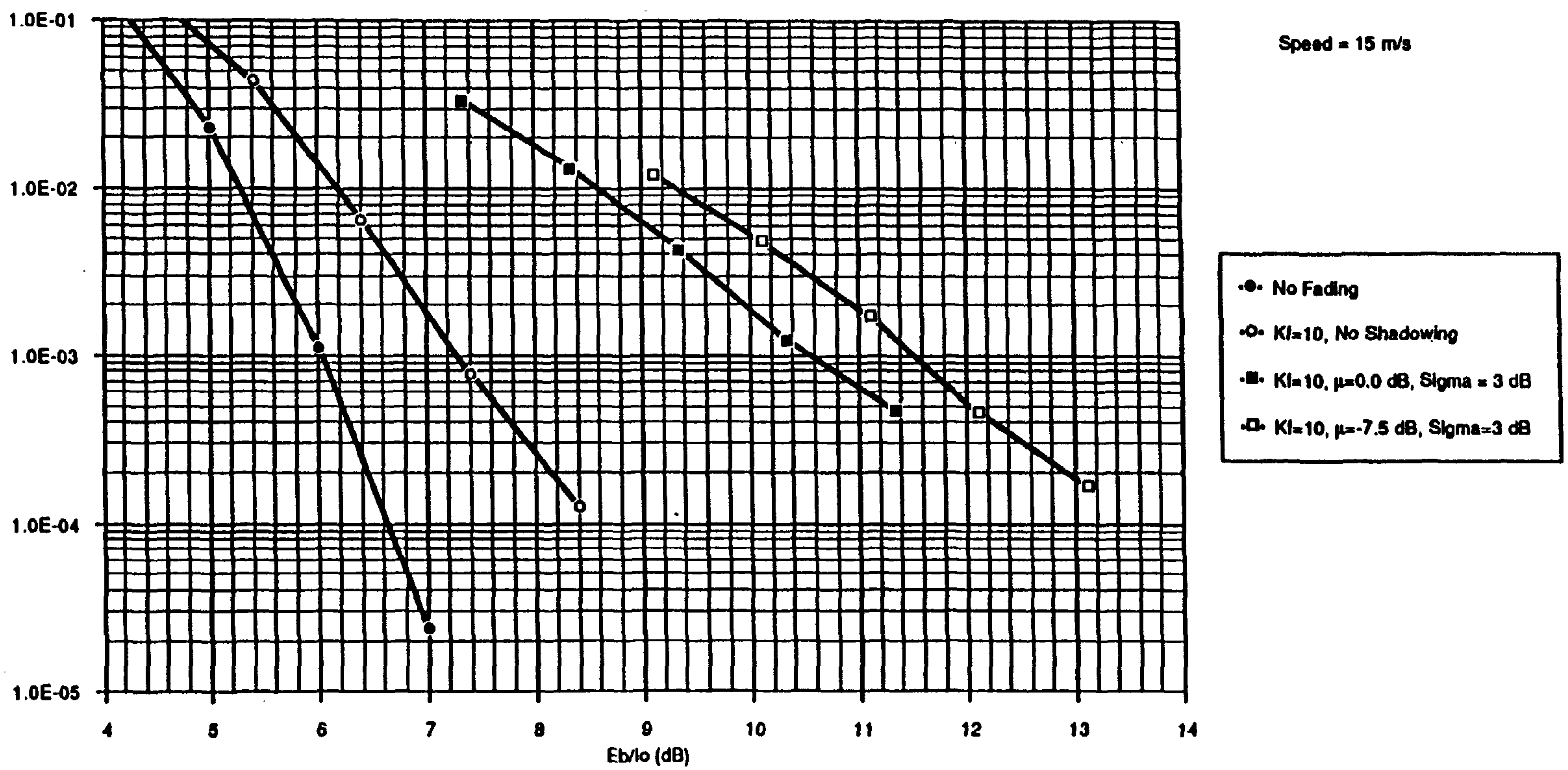


Figure 6-11
Mobile to Hub Bit Error Rate (DPSK)

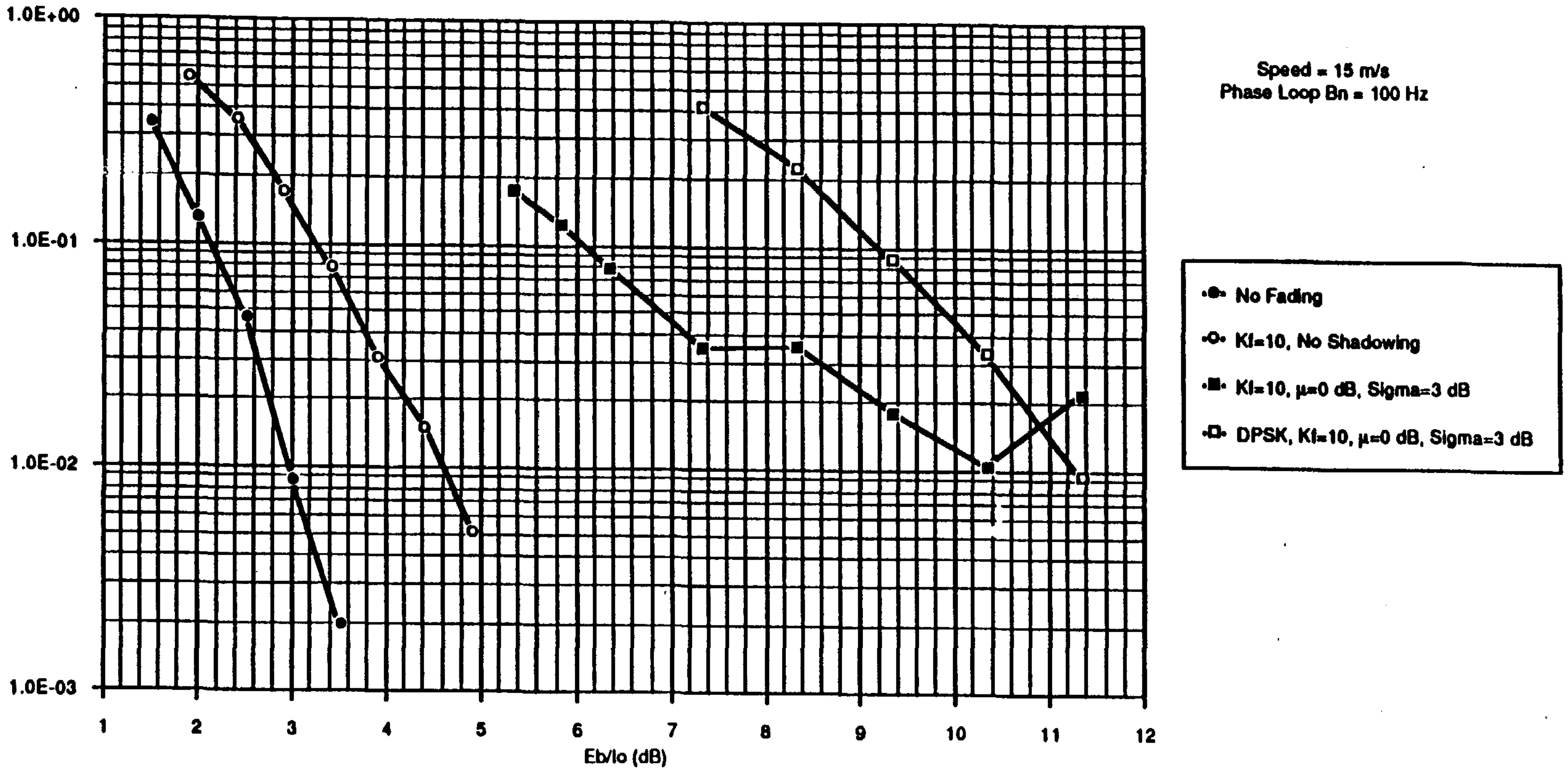


Figure 6-12
Mobile to Hub Frame Error Rate (BPSK)

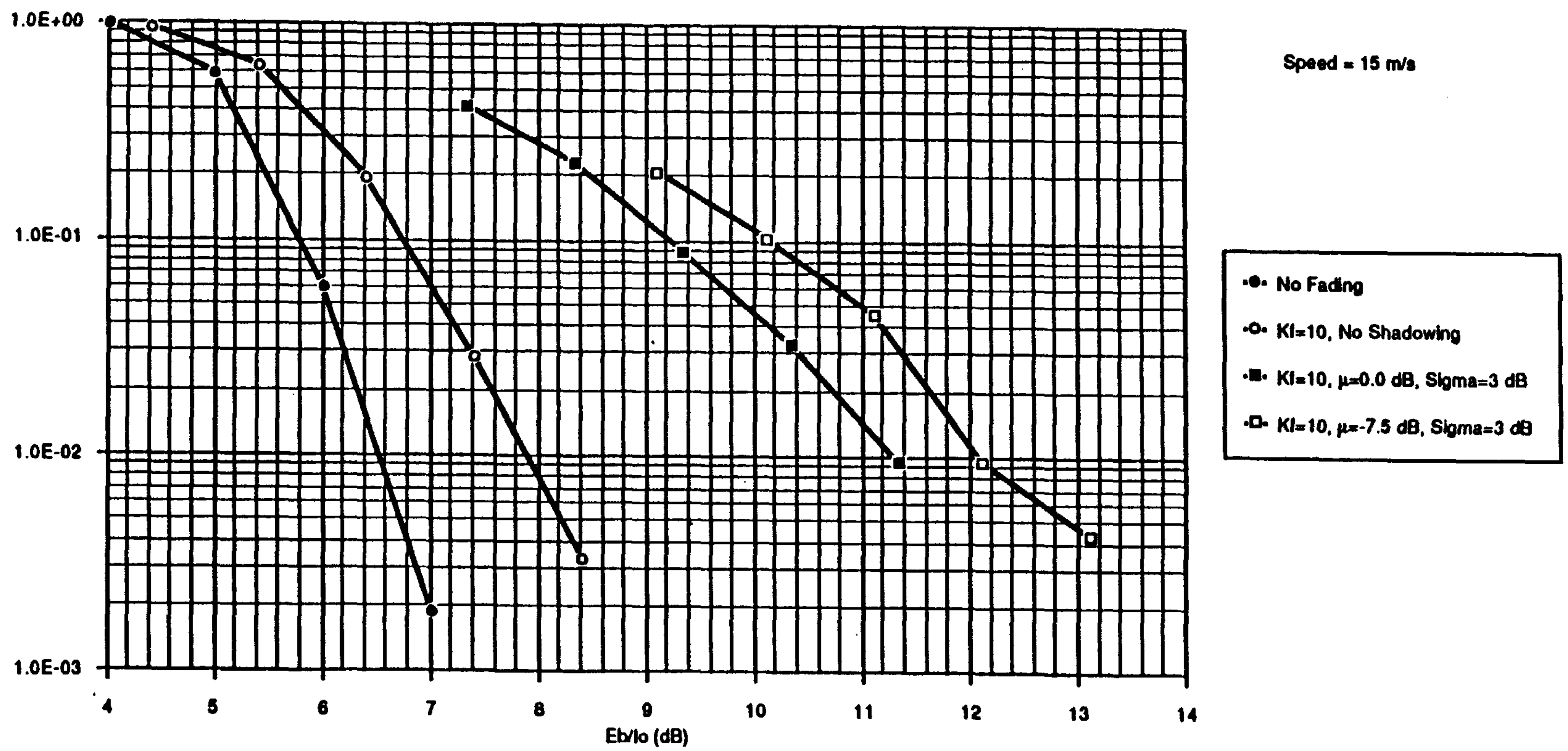


Figure 6-13
Mobile to Hub Frame Error Rate (DPSK)

System Link Budgets

This section uses the results of the simulations of the previous two sections to estimate the system capacity. A mix of users is assumed and that mix combined with the simulations are used to compute the Fading Capacity Margin. Next, these are used with other data in the system link budgets to calculate overall system capacity.

Capacity Margin

To calculate the effects of fading, we coin the term "Capacity Margin". Capacity Margin is defined as the amount by which the system capacity must be reduced in order to both provide marginal users additional Eb/(Io+No) margin and, at the same time, keep the Eb/(Io+No) of the nominal user a constant.

Tables 7-1 and 7-2 show these calculations. The first four columns are based on the assummed mix of users described more fully below. The margin is the additional Eb/(Io+No) required compared to an unfaded user with a 97% availability. *Weighted Percent* is calculated by multiplying the "Percent of Users" by $10^{(Margin/10)}$. The sum of the *Weighted Percents* is the amount by which the nominal Eb/(Io+No) would have been degraded if no adjustment in system capacity were made. If, on the other hand, system capacity is reduced by this factor, then we return to the original, nominal, Eb/(Io+No). This factor expressed in dB is the Capacity Margin. Finally, the last column is the actual contribution of each group of users to the interference total. It is calculated by reducing the *Weighted Percent* numbers by the *Capacity Margin.*

Table 7-1 — Return Link (Mobile to Hub) Capacity Margin Calculations

Percent of Users	K	sigma (dB)	mean (dB)	Margin (dB)	Availability	Weighted Percent	Interference Contribution
80%	40.0	0.0	0.0	0.2	97%	83.91%	61.42%
14%	10.0	0.0	0.0	1.3	97%	18.95%	13.87%
6%	10.0	3.0	-7.5	7.5	90%	33.77%	24.72%
					Total	136.63%	100.00%
					Return Capacity Margin	1.36 dB	

Table 7-2 — Forward Link (Hub to Mobile) Capacity Margin Calculations

Percent of Users	K	sigma (dB)	mean (dB)	Margin (dB)	Availability	Interference Contribution	Interference Contribution
80%	40.0	0.0	0.0	0.1	97%	81.86%	59.92%
14%	10.0	0.0	0.0	0.3	97%	15.00%	10.98%
6%	10.0	3.0	-7.5	3.5	90%	13.43%	9.83%
					Total	110.30%	80.73%
					Return Capacity Margin	0.43 dB	

Assumptions:

97% Availability is defined as a Frame Error Rate of 3% and 90% Availability is defined as 10% Frame Error Rate. This Chart assumes 80% Highway and Aircraft (K=40), 20% Suburban/Rural (14% K=10, 6% K=10, μ=7.5, s=3) with all users at 34 mph (15 meteres/sec).

Link Budgets

Table 7-3 provides a summary of the capacities that are calculated in the following link budgets. There is not a direct scaling in the channel capacity with data rate due to the details of the preambles and framing used.

Table 7-3 — Capacity Summary

Data Rate	Forward Capacity	Return Capacity	Minimum Capacity Forwoard or Return
16,000	2,935	2,805	2,805
9,600	4,765	4,575	4,575
4,800	8,949	8,590	8,590
2,400	15,952	15,875	15,875

L-Band Forward Link Budget

Table 7-4 is the L-Band Forward Link Budget. This section describes each item in the budget. Note that the total capacity in each case is the free variable that is adjusted to keep a minimum "Excess Link Margin" of 3.0 dB.

SSPA Power — Solid State Power Amplifier Power. These numbers were provided by Hughes as realistic for the MSS satellite.

Power Loss — This is the power lost from SSPA to antenna.

Backoff — This is the amount the SSPA needs to be backed out of saturation. To control excess noise (interference) production, the CDMA systems need at least 3.0 dB of backoff. Rather than use a backoff term, it has been assumed that a linearizer is used and that the SSPA Power as stated above is output power of the linearized SSPA. For these reasons, the entries have a value of 0.0 dB.

Spacecraft Antenna Gain — The gain of the L-Band transmit antenna. The gain for the CDMA antenna is 0.5 dB higher than an equivalent FDMA antenna because of the use of an untapered phased array with a narrower main lobe. This gives a pattern that is approximately sin(x)/x in shape with higher sidelobes (perfectly acceptable for CDMA) and a larger boresight gain.

EIRP — Effective Isotropic Radiated Power. This the sum of the previous four items in dB.

Total Capacity — This is the maximum number of voice calls that can be sent simultaneously. It is the maximum of bandwidth or power/noise limitations.

Voice Duty Cycle — The average amount of time a speaker is speaking on one direction of a full duplex link. 40% is assumed for all cases.

Table 7-4 — L-Band Forward Link Budget Calculations

	CDMA CVSD, Omni	CDMA LPC, Omni	CDMA LPC, Omni	CDMA LPC, Omni
SSPA power	28.0 dBW	28.0 dBW	28.0 dBW	28.0 dBW
Power Loss	-1.0 dB	-1.0 dB	-1.0 dB	-1.0 dB
Backoff	0.0 dB	0.0 dB	0.0 dB	0.0 dB
Spacecraft Antenna Gain	37.2 dB	37.2 dB	37.2 dB	37.2 dB
EIRP	64.2 dBW	64.2 dBW	64.2 dBW	64.2 dBW
Total Capacity	2935 Erlangs	4765 Erlangs	8949 Erlangs	15952Erlangs
Voice Duty Cycle	40%	40%	40%	40%
-10•log(N•Duty Cycle)	-30.7 dB	-32.8 dB	-35.5 dB	-38.0 dB
Pilot Power	-0.3 dB	-0.3 dB	-0.3 dB	-0.3 dB
Uplink Drive Loss	0.0 dB	0.0 dB	0.0 dB	0.0 dB
EIRP/channel	33.2 dBW	31.1 dBW	28.4 dBW	25.9 dBW
Path Loss	-187.5dB	-187.5 dB	-187.5 dB	-187.5dB
Polarization Loss	-0.5 dB	-0.5 dB	-0.5 dB	-0.5 dB
E/S Antenna Gain	4.0 dB	4.0 dB	4.0 dB	4.0 dB
Data Rate	16,000bits/sec	9,600 bits/sec	4,800 bits/sec	2,400bits/sec
-10 log(Data Rate)	-42.0 dB/Hz	-39.8 dB/Hz	-36.8 dB/Hz	-33.8 dB/Hz
Power to Preambles	-0.2 dB	-0.3 dB	-0.6 dB	-1.1 dB
Eb	-193.0dBW/Hz	-193.0 dBW/Hz	-193.0 dBW/Hz	-193.0dBW/Hz
LNA Temperature	100 °K	100 °K	100 °K	100 °K
Antenna Noise	50 °K	50 °K	50 °K	50 °K
UpLink Thermal Noise	0 °K	0 °K	0 °K	0 °K
Total Thermal Noise	150 °K	150 °K	150 °K	150 °K
Thermal Noise Density, No	-206.8dBW/Hz	-206.8 dBW/Hz	-206.8 dBW/Hz	-206.8dBW/Hz
EIRP + E/S Gain - Losses	-119.8dBW	-119.8 dBW	-119.8 dBW	-119.8dBW
% of Satellite Power in Beam	15%	15%	15%	15%
10•log(% of Sat. Power)	-8.2 dB	-8.2 dB	-8.2 dB	-8.2 dB
Spreading Bandwidth	8.064E+06 Hz	8.064E+06 Hz	8.064E+06 Hz	8.064E+06 Hz
-10•log(Spreading BW)	-69.1 dB/Hz	-69.1 dB/Hz	-69.1 dB/Hz	-69.1 dB/Hz
Add. Noise due to Limiting	0.0 dB	0.0 dB	0.0 dB	0.0 dB
Pseudo-Noise Density, Io	-197.1dBW/Hz	-197.1 dBW/Hz	-197.1 dBW/Hz	-197.1dBW/Hz
Thermal, Eb/No	13.8 dB	13.8 dB	13.8 dB	13.8 dB
Pseudo-Noise, Eb/Io	4.1 dB	4.1 dB	4.1 dB	4.1 dB
Combined, Eb/(No+Io)	3.7 dB	3.7 dB	3.7 dB	3.7 dB
Fading Allow. per User Dist.	-0.4 dB	-0.4 dB	-0.4 dB	-0.4 dB
Modem Implementation Loss	-0.5 dB	-0.5 dB	-0.5 dB	-0.5 dB
Eb/(No+Io) Minimum	2.4 dB	2.4 dB	2.4 dB	2.4 dB
Excess Link Margin	3.0 dB	3.0 dB	3.0 dB	3.0 dB

-10•log(N•Duty Cycle)
: This is the product of Total Capacity and Voice duty cycle expressed in dB.

Pilot Power
: This the amount that the downlink power must be reduced to support the shared pilot. It is calculated as:

$$\text{Pilot Power} = 10 \log_{10}\left(1 - \frac{0.01}{\%\ \text{Sat. Beam}}\right)$$

The factor of 0.01 comes from the -20 dB Ec/Io assumed for the pilot and the *% Sat. Beam* term is included to account for the pilot being shared among all of the beams.

Uplink Drive Loss
0.0 dB is assumed for all cases.

EIRP/Channel EIRP per active channel. EIRP ÷ (Total Capacity • Voice Duty Cycle) expressed in dBW.

Path Loss $1/r^2$ loss at L-Band from geosynchronous orbit to an average location in the 48 states.

Polarization Loss
Losses due to mismatches in polarization.

E/S Antenna Gain
Earth Station Antenna Gain. 4 dBi for the "omni" antenna.

Data Rate This is the information data rate used to transmit the voice signal. It is used to calculate an E_b and then later an E_b/N_0.

-10•log(Data Rate)
or $10 \cdot \log_{10}(1/\text{Data Rate})$. 1/Data Rate in dB/Hz.

Power to Preambles
This is the power that must be used to support the preambles that are not used directly to transmit data. It is the average loss in signal power used to transmit the preamble in each 50 millisecond frame. Because the average data rate is adjusted by the voice duty cycle, this factor must be adjusted also. The exact formula is:

$$\text{Power to Preambles} = -10 \log_{10}\left(1 + \frac{40 \text{ sym/preamble} \cdot 20 \text{ preambles/sec}}{\text{Data Rate} \cdot 3\text{sym/bit} \cdot \text{Voice Duty Cycle}}\right)$$

Eb E_b is the Energy of each received information bit. This is the sum of EIRP/Channel, Fading Loss, Path Loss, Polarization Loss, E/S Antenna Gain, -10•log(Data Rate) and Power to Preambles.

LNA Temperature
The excess noise temperature of the Low Noise Amplifier.

Antenna Noise
The noise temperature of the environment "seen" by the antenna. This is higher for an "omni" antenna because it "sees" more of the earth at 290°K. than a directional antenna that sees mostly the sky and deep space at ~10°K.

Uplink Thermal Noise
The noise contribution due to the Ku-Band uplink. This is assumed to be very small because of the high EIRP of the Hub at Ku-Band and the use of an FM link.

Total Thermal Noise
The sum of the previous three noise temperatures.

Thermal Noise Density, No
N_0 is $10 \cdot \log_{10}(\text{Total Thermal Noise} \cdot k)$ where k is Boltzmann's constant.

EIRP + E/S Gain – Losses
This is the total power received from the satellite by the mobile unit. This will be used for calculation of the "self noise", I_0 of the CDMA system.

% of Satellite Power in Beam
The "Noise Beam Width" of the satellite antenna pattern expressed as a

percentage of the 48 states. If a uniform distribution of users across the U.S. is assumed, then this is the percent of the satellite power seen at any one location.

10•log(% of Sat. Power)
: The above number in dB.

Spreading Bandwidth
: The chip rate of the spreading sequence. With a chip rate of 8.064 MHz, the spectrum of the modulation can be effectively contained in a 9.0 MHz spectral template.

-10•log(Spreading Bandwidth)
: The above number in dB/Hz.

Additional Noise due to Limiting
: The effect of an envelope limiter followed by a bandpass filter on a BPSK signal that is much smaller than the Gaussian noise is to reduce the E_b/N_0 of the signal by a factor of $\pi/4$ or 1.0 dB. The latest link budgets assume a linear power amplifier and therefore this term is 0.0 dB.

Pseudo-Noise Density, Io
: The sum of the above four numbers is the power of the pseudo-noise per Hertz (dBW/Hz).

Thermal, Eb/No
: E_b/N_0 in dB is $E_b - N_0$ in dB.

Pseudo-Noise, Eb/Io
: E_b/I_0 in dB is $E_b - I_0$ in dB.

Combined, Eb/(No+Io)
: To do this combination correctly, both $-E_b/N_0$ and $-E_b/I_0$ must be converted from dB scale to a linear scale, added and then converted back to a dB scale to get $-E_b/(N_0+I_0)$.

Fading Allowance per User Distribution
: This is the Capacity Margin calculated above.

Modem Implementation Loss
: The extra E_b/N_0 in dB needed above the theory to achieve 3% Frame Error Rate.

Eb/(No+Io) Minimum
: This is the Sinnal to Noise Ratio needed in an unfaded environment to produce a Frame Error Rate of 3%.

Excess Link Margin
: For a CDMA system, we must be careful to distinguish link margin from capacity margin. To do this analysis, we assume that signal energy E_b=1.0, that less link margin directly affects E_b/N_0 and that less link margin has no effect on E_b/I_0. Given that the following equation and definitions hold and all variables are known except for excess link margin, we can solve for the excess link margin, LM. That is the additional amount that we can attenuate the signal and still have minimum BER.

$$10^{-(E_b/N_{0\,theory} - M)/10} = 10^{-(E_b/I_0 + CM)/10} + 10^{-(E_b/N_0 - LM)/10}$$

where:

$E_b/N_{0\ theory} \equiv$ Theoretical E_b/N_0 needed for 3% FER

$M \equiv$ Modem Implementation Loss

$E_b/I_0 \equiv$ Signal to Interference Ratio

$CM \equiv$ Capacity Margin

$E_b/N_0 \equiv$ Signal to Thermal Noise from Channel

$LM \equiv$ Excess Link Margin

It is this solution that is used in the link budgets for CDMA excess link margin.

L-Band Return Link Budget

Table 7-5 contains the L-Band Return Link Budget. This section describes each item in the budget. Note that the total capacity in each case is the free variable that is adjusted (within bandwidth limitations) to keep a minimum Excess Link Margin of 3.0 dB.

SSPA Power: Solid State Power Amplifier Power. These were made large enough so they did not have a significant effect on capacity.

E/S Antenna Gain: Earth Station Antenna Gain. 4 dBi for the "omni" antenna.

Path Loss: $1/r^2$ loss at L-Band from an average location in the 48 states to geo - synchronous orbit.

Spacecraft Antenna Gain: The gain of the L-Band transmit antenna.

Data Rate: This is the information data rate used to transmit the voice signal. It is used to calculate an E_b and then later an E_b/N_0.

-10•log(Data Rate): or $10 \cdot \log_{10}(1/\text{Data Rate})$. 1/Data Rate in dB/Hz.

Eb: E_b is the Energy of each received information bit. This is the sum of HPA Power, E/S Antenna Gain, Path Loss, Spacecraft Antenna Gain and - 10•log(Data Rate).

Spreading Bandwidth: The chip rate of the spreading sequence. With a chip rate of 8.064 MHz, the spectrum of the modulation can be effectively contained in a 9.0 MHz spectral template.

10•log(Data Rate/Spreading BW): This is the processing gain of the spread spectrum system in dB. This can be used to convert any one user's E_b to the I_0 contribution of that user.

% of Users in Beam: The "Noise Beam Width" of the satellite antenna pattern expressed as a percentage of the 48 states. If a uniform distribution of users across the U.S. is assumed, then this is the percent of users seen by any one beam.

Table 7-5 — L-Band Return Link Budget Calculations

	CDMA CVSD, Omni	CDMA LPC, Omni	CDMA LPC, Omni	CDMA LPC, Omni
HPA Power	3.0 dBW	1.0 dBW	-2.0 dBW	-2.0 dBW
E/S Antenna Gain	4.0 dB	4.0 dB	4.0 dB	4.0 dB
Path Loss	-187.5dB	-187.5 dB	-187.5 dB	-187.5dB
Spacecraft Antenna Gain	37.2 dB	37.2 dB	37.2 dB	37.2 dB
Data Rate	16,000bits/sec	9,600 bits/sec	4,800 bits/sec	2,400bits/sec
-10•log(Data Rate)	-42.0 dB/Hz	-39.8 dB/Hz	-36.8 dB/Hz	-33.8 dB/Hz
Eb	-185.3dBW/Hz	-185.1 dBW/Hz	-185.1 dBW/Hz	-182.1dBW/Hz
Spreading Bandwidth	8.064E+06 Hz	8.064E+06 Hz	8.064E+06 Hz	8.064E+06 Hz
10•log(Data Rate/Spr. BW)	-27.0 dB	-29.2 dB	-32.3 dB	-35.3 dB
% of Users in Beam	15%	15%	15%	15%
Voice Duty Cycle	40%	40%	40%	40%
Preamble Power	0.2 dB	0.3 dB	0.6 dB	1.1 dB
Total Capacity	2,805Erlangs	4,575 Erlangs	8,590 Erlangs	15,875Erlangs
Cap.•Duty Cycle•% of Users	168 Erlangs	275 Erlangs	515 Erlangs	953 Erlangs
10•log(above)	22.3 dB	24.4 dB	27.1 dB	29.8 dB
Pseudo-Noise Density, Io	-189.9dBW/Hz	-189.7 dBW/Hz	-189.7 dBW/Hz	-186.5dBW/Hz
Total Sat. Noise Temperature	398.0 °K	398.0 °K	398.0 °K	398.0 °K
Thermal Noise Density, No	-202.6dBW/Hz	-202.6 dBW/Hz	-202.6 dBW/Hz	-202.6dBW/Hz
Thermal, Eb/No	17.3 dB	17.5 dB	17.5 dB	20.5 dB
Pseudo Noise, Eb/Io	4.6 dB	4.6 dB	4.6 dB	4.4 dB
Combined, Eb/(No+Io)	4.4 dB	4.3 dB	4.4 dB	4.3 dB
Fading Allow. for User Dist.	-1.4 dB	-1.4 dB	-1.4 dB	-1.4 dB
Modem Implementation Loss	-0.5 dB	-0.5 dB	-0.5 dB	-0.5 dB
Eb/(No+Io) Minimum	2.4 dB	2.4 dB	2.4 dB	2.4 dB
Excess Link Margin	3.0 dB	3.0 dB	3.0 dB	3.0 dB
Min. Cap., For. or Ret.	*2,805 Erlangs*	*4,575 Erlangs*	*8,590 Erlangs*	*15,875 Erlangs*

Voice Duty Cycle
: The average amount of time a speaker is speaking on one direction of a full duplex link. 40% is assumed for all cases.

Total Capacity
: This is the maximum number of voice calls that can be sent simultaneously. It is the maximum of bandwidth or power/noise limitations.

Capacity•Duty Cycle•% of Users
: The effective number of users in any one beam at one time.

10•log(above) The above in dB.

Pseudo-Noise Density, Io
: E_b + Processing Gain + Effective number of users.

Total Satellite Noise Temperature
: Noise temperature of the satellite at L-Band from Hughes MSS FCC filing.

Thermal Noise Density, No
: N_0 is $10 \cdot \log_{10}$(Total Thermal Noise • k) where k is Boltzmann's constant.

Thermal, Eb/No
: E_b/N_0 in dB is $E_b - N_0$ in dB.

Pseudo-Noise, Eb/Io

E_b/I_0 in dB is $E_b - I_0$ in dB.

Combined, Eb/(No+Io)

To do this combination correctly, both $-E_b/N_0$ and $-E_b/I_0$ must be converted from dB scale to a linear scale, added and then converted back to a dB scale to get $-E_b/(N_0+I_0)$.

Fading Allowance due to User Distribution

This is the Capacity Margin calculated above.

Modem Implementation Loss

The extra E_b/N_0 in dB needed above the theory to achieve 3% Frame Error Rate.

Eb/(No+Io) Minimum

This is the Signal to Noise Ratio needed in an unfaded environment to produce a Frame Error Rate of 3%.

Excess Link Margin

For a CDMA system, we must be careful to distinguish link margin from capacity margin. To do this analysis, we assume that signal energy E_b=1.0, that less link margin directly affects E_b/N_0 and that less link margin has no effect on E_b/I_0. Given that the following equation and definitions hold and all variables are known except for excess link margin, we can solve for the excess link margin, LM. That is the additional amount that we can attenuate the signal and still have minimum BER.

$$10^{-(E_b/N_{0\,\text{theory}} - M)/10} = 10^{-(E_b/I_0 + CM)/10} + 10^{-(E_b/N_0 - LM)/10}$$

where:

$E_b/N_{0\,\text{theory}} \equiv$ Theoretical E_b/N_0 needed for 3% FER

$M \equiv$ Modem Implementation Loss

$E_b/I_0 \equiv$ Signal to Interference Ratio

$CM \equiv$ Capacity Margin

$E_b/N_0 \equiv$ Signal to Thermal Noise from Channel

$LM \equiv$ Excess Link Margin

It is this solution that is used in the link budgets for CDMA excess link margin.

Appendix I
Signal-to-Noise Ratio in CDMA Systems

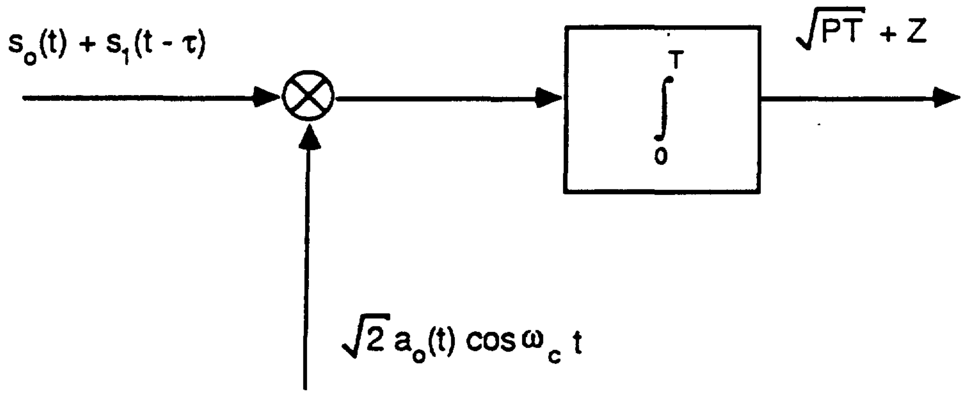
Let us assume that User #1 is the interference for User #0 and only two users are active. The transmitted signal for User # 1 is

$$s_1(t) = \sqrt{\frac{2P}{T}}\, a_1(t)\, b_1(t) \cos(\omega_c t + \theta)\,, \tag{1}$$

where

$$a_1(t) = \sum_{k=-\infty}^{+\infty} a_{1k} P_{Tc}(t - kT_c), \quad 1/T_c = \text{chip rate},$$

$$b_1(t) = \sum_{k=-\infty}^{+\infty} b_{1k} P_T(t - kT), \quad 1/T = \text{data rate}.$$



At the receiver, under the condition that $b_{10} = 1$, the output of the integrate-and-dump is equal to

$$\sqrt{PT} + Z$$

The random variable Z is the interference and is equal to

$$Z = \sqrt{\frac{P}{T}} \int_{0}^{T} a_1 (t - \tau) b_1 (t - \tau) a_0 (t) \cos \theta \; d t \tag{2}$$

θ = uniformly distributed $[0, 2\pi]$

τ = uniformly distributed $[0, T]$.

then the interference energy is

$$E [Z^2] = \frac{P}{T} E \{ \int_0^T \int_0^T a_1 (t - \tau) a_1(u - \tau) a_0 (t) a_0(u)$$

$$\cdot b_1 (t - \tau) b_1 (u - \tau) \cos^2 \theta \, du \, dt \} \tag{3}$$

$$= \frac{P}{2T} \int_0^T \int_0^T R_{a_1}(t - u) R_{a_0}(t - u) R_{b_1}(t - u) \, dt \, du \tag{4}$$

$$= \frac{P}{2} \int_{-T}^{T} (1 - \frac{|\sigma|}{T}) R^2_{a_0}(\sigma) R_{b_1}(\sigma) \, d\tau \tag{5}$$

The integrand in (4) is a function of $\sigma = t - u$, thus (5) simply follows.

Since

$$R_{b_1}(\sigma) = (1 - \frac{|\sigma|}{T}), \; |\sigma| < T$$

then (5) becomes

$$E [Z^2] = \frac{P}{2} \int_{-T}^{T} (1 - \frac{|\sigma|}{T})^2 R^2_{a_0}(\sigma) \, d\sigma \tag{6}$$

Since $R_{a_o}(\sigma) \approx 0$ for $\sigma \geq T$ if $T >> T_c$ and

$$\left(1 - \frac{|\sigma|}{T}\right)^2 \sim 1 \quad |\sigma| << T$$

we can approximate $E[Z^2]$ as follows

$$E[Z^2] \sim \frac{P}{2} \int_{-\infty}^{+\infty} R_{a_o}(\sigma)\, d\sigma \qquad (7)$$

where

$$R_{a_o}(\sigma) = E\{ a_o(t + \sigma)\, a_o(t) \}.$$

and $a_0(t)$, $a_1(t)$ are independent random "PN" sequences.
If $P_{Tc}(t)$ is a rectangular pulse of duration T_c secs, then Eq (7) becomes

$$Z[Z^2] = \frac{P}{2} \int_{-\infty}^{+\infty} R^2_{a_o}(\sigma)\, d\sigma = \frac{P}{2} \cdot \frac{2}{3} T_c$$

and the signal-to-interference ratio is

$$\frac{E_b}{I_o} = \frac{PT}{E[Z^2]} = \frac{2T}{2/3\, T_c} = 3\frac{T}{T_c} = 3N$$

where $N = T/T_c$. If $P_{Tc}(t) = \sin(\pi t/T_c)$ then

$$\int_{-\infty}^{+\infty} R^2_{a_o}(\sigma)\, d\sigma = \frac{15 + 2\pi^2}{6\pi^2} T_c$$

and

$$\frac{E_b}{I_o} = 3.41\ N$$

A gain of 13.6% with respect to the rectangular pulse case.

With K users and white noise of spectral density N_o (single-sided) the SNR is

$$\text{Rect. pulse:} \quad SNR = \left(\frac{K-1}{3N} + \frac{N_o}{2E_b}\right)^{-1}$$

$$\text{Sine pulse:} \quad SNR = \left(\frac{K-1}{3.41N} + \frac{N_o}{2E_b}\right)^{-1}$$

In the following we show that in a bandlimited channel E $[Z^2]$ is lower bounded.

<u>Theorem.</u> If a signal x(t) is bandlimited to frequencies $|f| \leq W$, i.e., $|S_x(f)| = 0$ for $|f| > 0$ then

$$\frac{1}{R_x^2(o)} \int_{-\infty}^{+\infty} R_x^2(t)\, dt \geq \frac{1}{2W}$$

<u>Proof:</u> By Parseval's relation

$$\int_{-\infty}^{+\infty} R_x^2(t)\, dt = \int_{-\infty}^{+\infty} |S_x(f)|^2\, df$$

and Schwarz inequality

$$\int_{-W}^{W} |S_x(f)|^2 \, df \, . \int_{-W}^{W} 1 \, . \, df \geq \left[\int_{-W}^{W} S_x(f) \, . \, 1 \, df \right]^2$$

or

$$\int_{-\infty}^{+\infty} R_x^2 (t) \, dt \, . \, 2W \geq R_x^2(o) \qquad \text{QED}$$

If the pulse is normalized to have unit energy then $R_x(o) = 1$ and Eq. (7) becomes

$$E\,[Z^2] \geq \frac{P}{2} \cdot \frac{1}{2W}$$

and equality holds for a pulse proportional to 1 for $|f| \leq W$, i.e.,

$$x(t) = \text{sinc}\,(2W\,t).$$

The SNR is therefore upper-bounded as follows

$$SNR \leq \left(\frac{K-1}{2 \, . \, 2WT} + \frac{N_o}{2E_b}\right)^{-1}$$

and the bound, achieved with the sinc (2W t) pulse, $W = 1/2T_C$, is

$$SNR = \left(\frac{K-1}{2N} + \frac{N_o}{2E_b}\right)^{-1}$$

At this point we can compare the performance in terms of signal-to-noise ratio of a SSMA system with different pulse shapes. We assume that the channel is specified by a spectral template, i.e. the channel bandwith is 9 MHz and 30 dB attenuation is required outside the bandwidth. In this case the chip rate for different pulse shapes has to be adjusted so that the power spectrum of the transmitted signal fits the spectral template. Note that MSK modulation can be obtained by using staggered sine pulses .

In Figs.I-1 - I-4 we have plotted the power spectral density for different pulse shapes and adjusted the chip rate to satisfy the channel bandwidth constraint.

Finally, in Table I we have calculated the capacity C in number of users for different pulse shapes at $E_b/I_0 = 4$ dB. The baseline pulse shape here is the sinc pulse, the pulse shape actually implemented is that produced by a 5-th order elliptic filter. As we can see from Table I this choice produces a loss of only 0.4 dB with respect to the theoretical optimum.

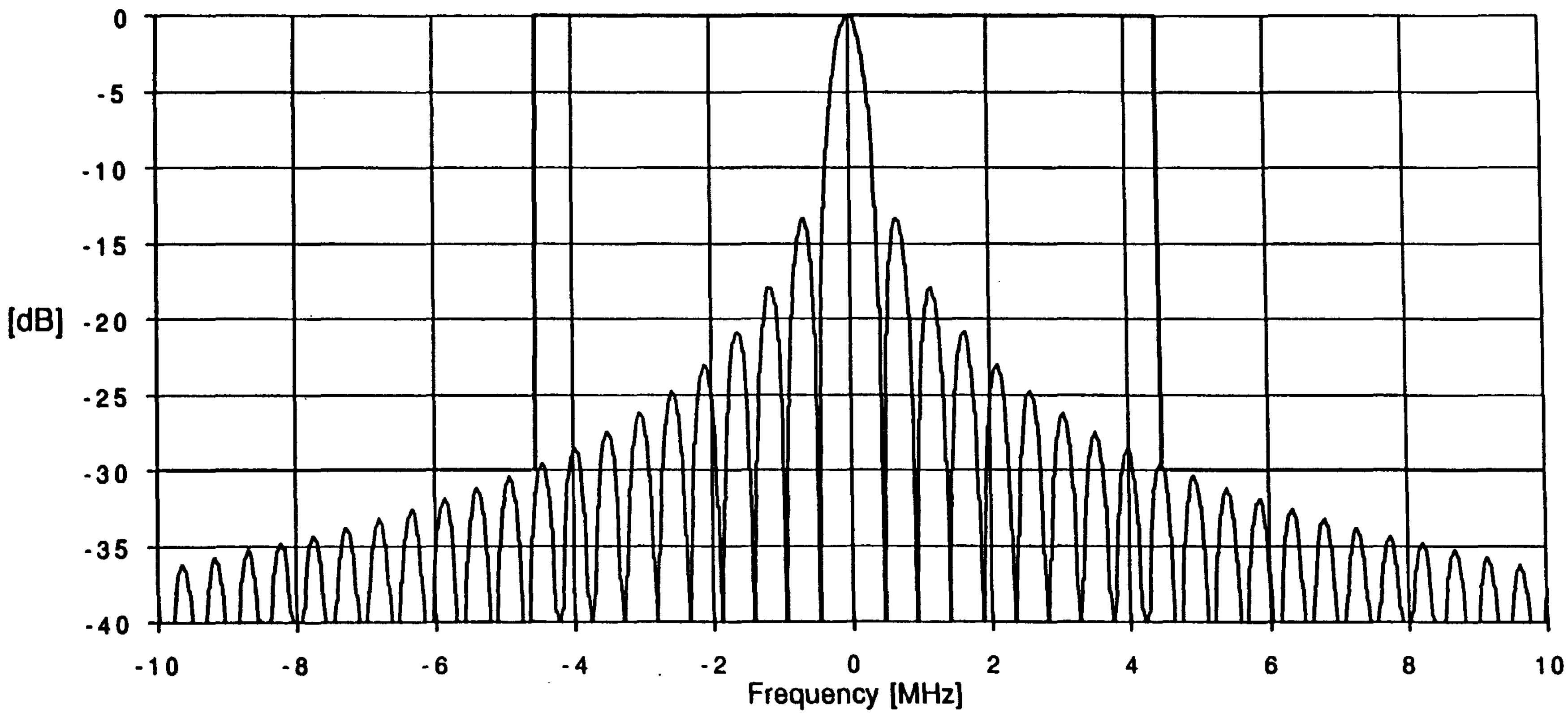


Figure I-1
Rectangular Pulse: Chip Rate = 468 Kcps

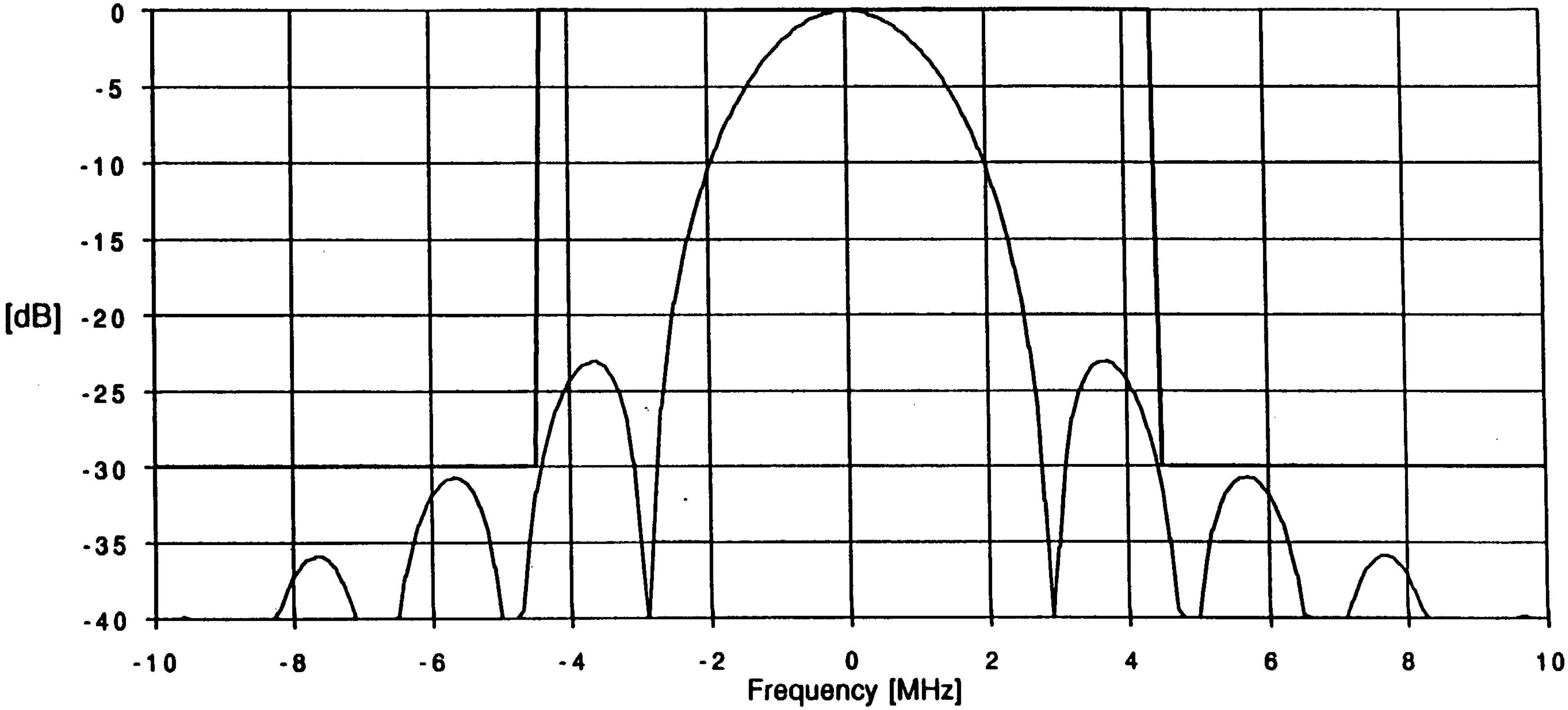


Figure I-2
Sine Pulse: Chip rate = 1.8 Mcps

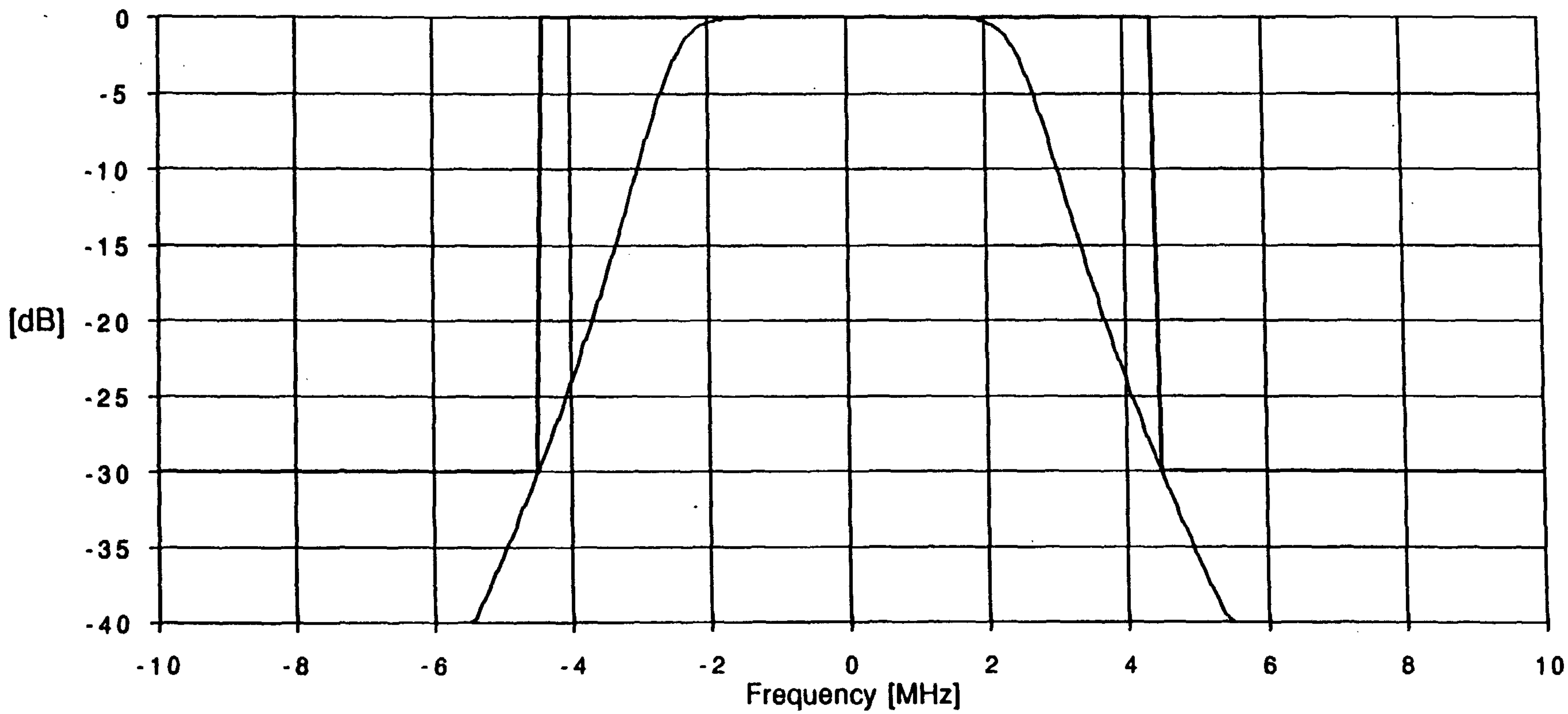


Figure I-3
Butterworth 6-pole: Chip Rate = 5.1 Mcps

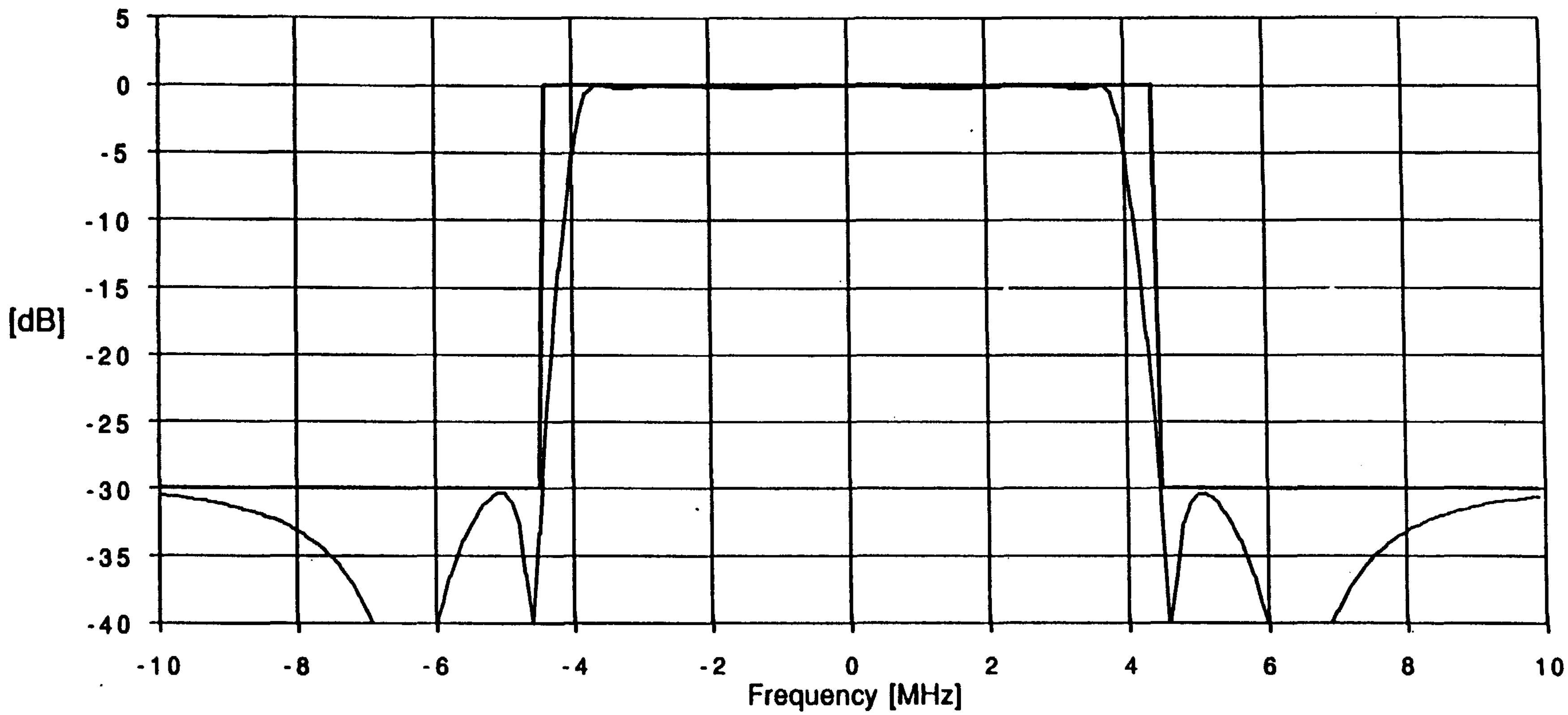


Figure I-4
Elliptic 5-th order: Chip Rate = 8.064 Mcps

Table I

CHANNEL BANDWIDTH = 9 MHz DATA RATE = 9600 bps

Pulse Shape	I/Tc	Chip Rate [Mcps]	$N = \frac{\text{Chip Rate}}{\text{Data Rate}}$	Eb/Io for 1 interferer	C (Eb/Io = 4 dB)	Loss [dB]
$\mathrm{sinc}(\pi t/T_c)$	1	9	937.5	2N=32.8 dB	759	0
Elliptic 5	0.98	8.064	840	2.04N=32.3 dB	676	0.4
BW6	0.906	5.1	531	2.2N=30.7 dB	468	2.1
$\sin(\pi t/T_c)$	0.586	1.8	187.5	3.4N=28 dB	252	4.8
$\mathrm{rect}(t/T_c)$	0.667	0.468	50.6	3N=21.8	60	11

Appendix II
Production Unit Cost Estimates

This appendix estimates the factory cost of the production of Mobile Unit Terminal. This estimate is done in two ways: First a Δ estimate is done based on the cost estimates included in the 30 April 1985 filing by Hughes for a Land Mobile Satellite System to the FCC. Table II-1 is a summary of that estimate. All of the cost figures are the same as those form the filing except for the DAMA Processor and the Omni Antenna. The filing listed a cost of $200 for the DAMA Processor. It is*QUALCOMM's* opinion that, in the light of current microprocessor costs and the potential volume involved, that this price is too high. Therefore, this cost has been reduced to $100. The filing listed the cost of a UHF Omni Antenna as $30. Because of the size differences between L-Band and UHF antennas, *QUALCOMM* feels comfortable reducing this cost to $25.

Table II-1 — Δ Cost Estimate based on 30 April 1980 Hughes Filing

Item	Cost
Basic Radio (UHF)	$931
RF Cavity (L-Band – UHF)	($35)
UHF RF Amplifier Filter	($106)
L-Band RF Amplifier Filter	$125
10 Watt UHF PA	($140)
10 Watt L-Band PA	$250
L-Band Duplexer	$70
DAMA Processor	$100
Telephone Central Unit	$50
Omni Antenna (L-Band)	$25
Factory Cost of Terminal	$1,270

The Basic Radio in the filing estimates was an Analog Companded Single Side Band (ACSSB) terminal, which is different[1] in many ways from the CDMA terminal proposed here. As a check on the above estimate, a "new" estimate was made with rough, but reasonable, cost estimates for the major components of the CDMA terminal.

Table II-2 shows the "new" cost estimate. The estimates are based on a 1988 production quantity of 5000 units. These costs do not include any allowance for amortization of non-recuring design costs. Also assumed is the availability of one or two custom CMOS ICs designed specifically for the CDMA modulator and demodulator functions[2].

[1]It should be pointed out that although the modulation of the ACSSB terminal is analog, much of the signal processing that is done, is done in a high speed signal processing chip (TMS320). This is that same type of chip that would be used for the LPC voice codec in the CDMA terminal.

[2]These custom ICs will be designed for use in the Hub CDMA modems as well.

Table II-2 — "New" Cost Estimate

Item	Cost
Voice Codec	$400
Frequency Reference	$15
Modulator	$50
Demodulator	$200
Control µproc./Front Panel	$100
L-Band LNA/Filter	$125
10 Watt L-Band PA	$250
L-Band Duplexer	$70
L-Band Omni Antenna	$25
Power Supply/Enclosure	$50
Factory Cost of Terminal	$1,285